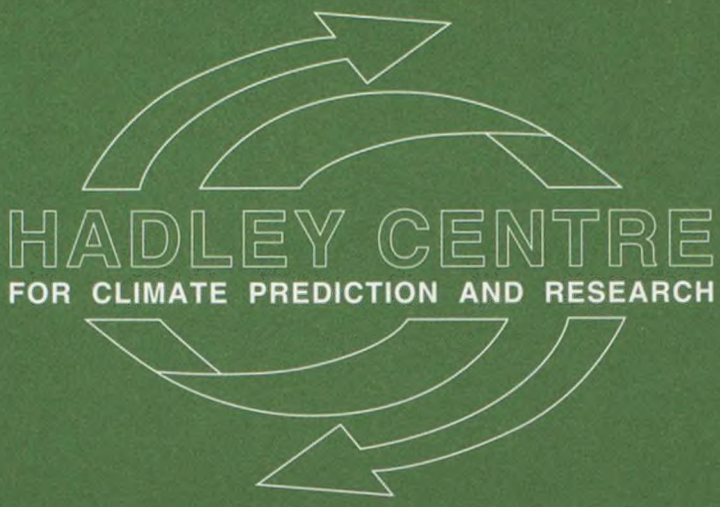

Understanding the sensitivity of a GCM simulation of Amazonian deforestation to the specification of vegetation and soil characteristics

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UNDERSTANDING THE SENSITIVITY OF A GCM SIMULATION OF AMAZONIAN DEFORESTATION TO THE SPECIFICATION OF VEGETATION AND SOIL CHARACTERISTICS

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1. Introduction

In recent years a number of general circulation model (GCM) experiments have been conducted to assess the impact of complete removal of the South American tropical rainforest on climate. A summary of the most recent GCM experiments is presented in Table 1 (an updated version of Pitman et al. (1993)) which shows that the experiments and results differ in many respects. Only changes in albedo and roughness are given here but the change in these parameters serves to illustrate the wide disparity in specified vegetation characteristics; the imposed decreases in roughness range from 0.76m to 2.57m and the increases in albedo from 5% to 8%. Results vary widely between experiments; increases in surface temperature range from 0.1°C to 3.8°C, decreases in precipitation from 15mmyear^{-1} to 640mmyear^{-1} (with the exception of Polcher and Laval (1994a) showing an increase in precipitation of 394mmyear^{-1}) and decreases in evaporation from 25mmyear^{-1} to 985mmyear^{-1}. As the wide variation in the specification of vegetation and soil characteristics may be responsible for explaining some of the difference in results it is desirable that some consensus be reached on the specification of these characteristics. The availability of extensive measurements taken during the Anglo-BRazilian Amazonian Climate Observation Study (ABRACOS) in Amazonia now provides this opportunity. Field missions and climate monitoring were carried out for three paired sites to represent different climatological regimes of the Amazonian rain forest; each pair of sites included one forested and one cleared area. The data collected as part of the field campaigns can be used to represent more realistically the soil and vegetation characteristics within GCMs (Wright et al. 1996) and longer term measurements of near-surface climate (Culf et al. 1996a) can be used to validate the modelled local climate.

This study builds on an earlier experiment by Lean and Rowntree(1993) (called LR in this paper), in which they evaluated the climatic consequences of complete removal of the Amazonian forest. Improvements are made in key areas of the land surface parametrizations together with more representative and accurate prescriptions of the parameter changes. Developments to the land surface scheme include the replacement of a single layer by a multilayer soil hydrology model, affording more realistic diurnal and

seasonal fluxes of evaporation and runoff, and the implementation of a canopy resistance model that is calibrated specifically for Amazonian forest and pasture. One other notable new feature of these simulations is the inclusion of monthly varying surface albedo. Culf et al. (1995) indicated that there is a strong seasonal dependence at the forest sites and some seasonal variation at pasture sites. As albedo is known to be one of the important parameters controlling the response to deforestation it is important to represent the change in this parameter as accurately as possible.

Amazonian deforestation is simulated here using the Hadley Centre GCM. First all grid points that are defined as tropical forest within the Amazon basin are given values for all vegetation characteristics as measured for the ABRACOS forest sites. The model is then integrated for a total of 10 years and 3 months to provide our reference simulation. Our deforestation scenario assumes that all grid points defined as tropical forest within the Amazon basin are replaced by pasture; a second integration is then performed identical to the reference experiment except that all values for the vegetation characteristics for these grid points are now taken from the ABRACOS measurements for the pasture sites. In addition to the changes made to the vegetation characteristics an additional change is made to one of the soil parameters to represent the observed compaction of soil and consequent reduction in infiltration following deforestation (Grimaldi et al. 1993; Reategui et al. 1990; Wright et al. 1996). This is implemented by reducing the maximum infiltration rate at the soil surface. It must be stressed that this is not a measured quantity and so some estimate of the likely reduction has to be made.

These experiments are some of the longest experiments of their kind (see Table 1) and this increases the statistical significance of the results. The length of the simulations also allows us to examine an important question concerning the influence of the initial boundary conditions on the final results raised by Pitman et al (1993) and Henderson-Sellers et al. (1993). They examined the length of time required for a coupled land surface scheme and climate model to adjust to imposed changes in the land surface characteristics and found that the period of adjustment ranged from 12 months to 3 years

depending on the climate variable considered with the longest period attributable to the root zone soil-water. To present a more plausible scenario for the deforested climate it is important to examine only those results that have reached an equilibrium state.

In simulating deforestation, changes to a number of vegetation characteristics are made together. This makes it difficult to identify the mechanisms that are responsible for controlling the climatic response. It is therefore instructive to try and build up the overall picture from the response to a number of single component changes. With limited resources it is not possible to examine the response to each of the vegetation characteristics separately and so it was decided to focus on roughness and albedo. Many studies have emphasised the importance of these two parameters (Dirmeyer and Shukla 1994; Pitman et al. 1993; Lean and Warrilow 1989; Dickinson and Henderson-Sellers 1988) but the sensitivity of the climate to changes in these parameters is still poorly understood. The response to reduced roughness and increased albedo is examined in turn, and then an assessment is made of the extent to which these two parameters dominate the final deforested climate relative to the change in all other vegetation characteristics. To achieve this a further experiment was performed identical to the deforestation scenario except that no change was made to the maximum infiltration rate. This experiment was also designed to provide a clearer indication of the sensitivity of the final deforested climate to the change in the maximum infiltration rate at the soil surface - a change which is poorly defined.

In the following sections a description of the Hadley Centre model is given in section 2, followed by an outline of the experiments in section 3. In section 4 use is made of climatological observations together with more recent near-surface climate measurements for the ABRACOS sites to validate the modelled climate over Amazonia. Results are presented from each of the individual experiments in section 5, building up to the full deforestation scenario. Finally discussion and summary are given in section 6.

2. Model description

The Hadley Centre model, the climate version of the Meteorological Office Unified Forecast/Climate GCM, used in these experiments, has been described in some detail by Jones et al. (1995). The atmospheric model has 19 layers spaced unevenly in the vertical to give optimum resolution in terms of pressure in the upper troposphere and stratosphere, and near the surface. The horizontal mesh is 2.5° latitude by 3.75° longitude, the same as used by LR. The dynamics use a two-step Heun scheme for horizontal advection with fourth order accuracy, formulated in terms of total water (vapour plus liquid and frozen cloud water) and liquid water temperature (temperature adjusted to allow for the latent heat of cloud water and ice).

The physics of the model is similar to that of the model used by LR. The main differences may be summarised as below:

- Cloud optical properties are computed as a function of the liquid and ice cloud water contents, with cloud assumed to be liquid for temperature above 0°C, and ice below -15°C with mixed phase cloud in between.
- The convection scheme has been extended to include representation of a downdraught (Gregory and Allen 1991)
- The atmospheric boundary layer occupies up to five layers (about 2.5km), depending on the position of the lowest statically stable layer. In unstable conditions, the increased vertical extent of turbulent eddies is accounted for by allowing non-local mixing (Smith 1993).

The model differs from that described by Jones et al. (1995) in certain aspects of the land surface parametrization:

- A 4-layer soil hydrology scheme based on Richards's equation is used, with the same vertical layer depths as used by Warrilow et al. (1986) for thermal processes.

The main reason for introducing this scheme is to improve the simulation of the diurnal and seasonal variation in the surface evaporation and runoff fluxes. Single layer models tend to overestimate this variation since they produce too little drainage from the root zone

in wet periods (when the soil moisture concentration in the root zone exceeds that below it) and too much drainage in dry periods (when the opposite is true). A multilayer model which extends below the root zone is better able to simulate these changes in drainage since it models the gradient in the soil water tension at the base of the root zone rather than assuming it to be zero (the boundary condition for a single layer model). In particular this means that the multilayer scheme can simulate the partial recharge of the root zone during dry periods by water from below.

- Over the South American tropical forest region, stomatal resistance is computed as a function of atmospheric variables (solar radiation, vapour pressure deficit below saturation and temperature) and soil moisture as described by Dolman et al. (1991) for forest and Wright et al. (1995) for pasture.

3. Experiment design

The following set of experiments was designed to give a more realistic portrayal of Amazonian deforestation compared with previous experiments together with providing a clearer indication of the mechanisms involved.

(1) FOREST - the reference experiment - a 10 year 3 month experiment with vegetation parameter values for all points in South America defined as tropical rainforest in the model (see Figure 1) taken from ABRACOS measurements of tropical rainforest.

(2) DEFOREST - the deforested experiment - a 10 year 3 month experiment with vegetation parameter values for all points in South America to be deforested (see Figure 1) taken from ABRACOS measurements of pasture. In addition the maximum infiltration rate at the soil surface is reduced (see below).

(3) PASTURE - a 5 year 3 month experiment as DEFOREST with changes to all vegetation parameters but without the change to the maximum infiltration rate.

(4) REDRGH - a 5 year 3 month experiment as FOREST except with roughness reduced from the FOREST value to the DEFOREST value and all other parameters unchanged.

(5) INCALB - a 5 year 3 month experiment as FOREST except with surface albedo increased from the FOREST value to the DEFOREST value and all other parameters unchanged.

Figure 1 shows the points on the 2.5° x 3.75° grid over South America that were defined as tropical forest. These points are based on the interpolation of the 1° x 1° grid of vegetation types as defined in the SiB model (Sellers et al. 1986) with some alterations based on more recent observations. Experiments were started at the beginning of December from initial fields generated by a data assimilation scheme for that time of year.

Table 2 shows the vegetation and soil parameters for FOREST and DEFOREST. The measured values of monthly-varying albedo as summarised by Culf et al (1995) were used for those points that have their dry season (and highest albedos) in southern winter or spring and the seasonal cycle was reversed for points where the observed rainfall cycle is approximately opposite, namely most points north of the equator. An area of western Amazonia centred near the equator which effectively has no dry season (a dry season was arbitrarily defined as having less than 300mm per 3 month season) was located, using the seasonal rainfall maps of Figueroa and Nobre (1990). For this region the lowest values of albedo (0.12 for FOREST and 0.17 for DEFOREST) were assigned throughout the year. All vegetation parameters are for the forest and pasture site at Manaus except values for albedo which are averages over the forest and pasture sites at Ji Paraná, Marabá and Manaus. Although field measurements have shown that root extraction occurs at depths greater than 3.5m, the rooting depth was limited to the maximum depth of soil (about 2.3m) in the model. The precise forms of the interactive resistance formulations were referenced in section 2.

At the time of this study only a few point measurements of soil parameters were available from the ABRACOS field campaigns and as variations in soil are apparent on much smaller scales than even vegetation characteristics it was decided that it was inappropriate to assume that these measurements could be taken as representative of the whole Amazon basin. Soil parameters were therefore taken from values given in our standard model; these parameters vary from grid point to grid point with average values for all deforested points as given in Table 2. All soil parameters were kept constant between FOREST and DEFOREST except the maximum infiltration rate at the surface which was reduced to

account for observations of reduced infiltration due to compaction of the soil by cattle following deforestation (Grimaldi et al. 1993; Reategui et al. 1990; Wright et al. 1996). The maximum infiltration rate is calculated by multiplying the saturated hydraulic conductivity for that grid point by an arbitrary factor which was chosen to be equal to 1.5 for all grid points in FOREST and 0.3 for all grid points in DEFOREST.

4. Model validation

In this section an assessment is made of the performance of the model's reference simulation, FOREST and deforestation experiment, DEFOREST for northern South America over a range of time scales. ABRACOS has made available a large amount of data that can be used in addition to standard climatologies to validate GCM simulations. Measurements taken during the ABRACOS field campaigns provide descriptions of the climates of forest and typical cleared areas (Eden et al. 1990; Uhl et al. 1988) within Amazonia; the three pairs of sites chosen were widely separated, Manaus in the state of Amazonas, Marabá in Para and Ji-Paraná in Rondonia, to represent a wide range of climatic conditions. Comparison will be restricted mainly to the forest sites because of the inappropriateness of comparing measurements for relatively small cleared areas directly with simulations of a completely deforested Amazonia. Culf et al. (1996a) showed that the observed seasonality of net surface radiation, temperature and specific humidity was very similar at the three forest and pasture sites, with net surface radiation reduced by about 10% at the pasture site relative to the forest site and smaller differences in temperature and specific humidity. As expected the model simulates much larger differences between the climate for FOREST and DEFOREST which are likely to be explained by the large difference in scale of forest clearance. All model results shown are averaged over 9 years with the first 1 year and 3 months of the experiments excluded (see section 5.a).

Figure 2 compares modelled rainfall for FOREST with extensive climatological observations taken over a number of years (Figueroa and Nobre 1990) for the southern hemisphere summer (December-February) and winter (June-August). Rainfall coverage

and amounts over northern South America are well simulated by the model in both these seasons. The most notable deficiencies are that the model fails to emulate some of the high rainfall totals recorded in the more mountainous regions of Colombia, Ecuador and Peru. The simulations for the other two seasons (not shown) are equally realistic. Figure 3 shows that modelled monthly mean rainfall agrees very well with observations for the three ABRACOS forest sites (as presented in Culf et al.(1996b)).

Figure 4 compares monthly mean climate variables for FOREST with measurements for just one of the sites, Ji-Parana. During May, June and July modelled surface net radiation corresponds fairly closely with observations but in all other months radiation is overestimated. This is a problem common to a number of GCMs and, as noted by LR, the model produces a good simulation of net radiation at the top of the atmosphere so this could be due to the omission of aerosols that can give substantial absorption of solar radiation in the boundary layer. Screen temperature agrees well with observations. The model captures the seasonal cycle of specific humidity but tends to maintain higher values than observed during June, July and August. Culf et al. reported that this observed large drop in specific humidity was due to the influence of cold fronts. Comparisons for the other two sites are equally good (not shown).

As a result of the deficiency in surface net radiation evaporation rates are overestimated and so to compare with observations it is more useful to normalise the evaporation rates by net radiation at the surface. Figure 5 compares normalised evaporation, for both FOREST and the reference experiment used by LR, with observations for Manaus (Shuttleworth 1988). The new reference experiment shows a marked improvement in modelling evaporation in all months but especially so from July to October when the model previously suffered from an excessive limitation for dry periods. This more realistic simulation can be attributed to a combination of the implementation of the new multilayer hydrology scheme (see section 2) together with the new formulation of stomatal resistance and the increased rooting depth (now 2.26m; previously a 1.27m rooting depth was used for forest).

Although as noted above, it is difficult to make direct comparison between observations for the cleared areas and DEFOREST, some indication of model performance can be gained. Wright et al. (1992) reported that during periods when there was negligible soil moisture limitation the observed evaporation rate for a pasture area was comparable with the transpiration rate from the forest, but during dry periods evaporation rates were much lower. The deforested simulation is able to reproduce this behaviour; Figure 6 shows the mean monthly evaporation for the FOREST and DEFOREST simulations - the average reduction in evaporation from 4.0 to 2.8mmday^{-1} during the relatively dry months of July through to September is comparable with the change reported by Wright et al. from 3.8 to 2.1mmday^{-1} during the 1990 dry season near Manaus. Correspondingly the modelled reduction in evaporation of 4.6mmday^{-1} to 4.0mmday^{-1} for the wet months of January through to April agrees well with the observations for a period following rain when the soil was moist (Figure 11(b) in Wright et al. (1992)). Bastable et al. (1993) reported on the much reduced efficiency in turbulent transfer due to reduced roughness and hence larger diurnal range in temperature over clearings compared with those observed over forest. Figure 7 shows the daily cycle in modelled surface temperature for Manaus, for FOREST and DEFOREST. These values can be compared with measurements of screen height temperature for a wet and dry period reported by Bastable et al., although strictly these variables are not the same. Two months are illustrated: the first for December, typical of a wet month (Figure 7(a)), shows a difference in the diurnal range of 9.1°C for DEFOREST and 6.9°C for FOREST which may be compared with the measured values for screen height temperature of 7.1°C and 5.3°C during a wet period. In contrast, during the relatively dry month of July (Figure 7(b)) there is a much larger difference in diurnal range, 11.4°C for DEFOREST and 7.3°C for FOREST compared with the measured values for screen height temperature of 12.7°C and 6.5°C during a dry period. However it should be noted that Bastable et al. showed that there was an increase in temperature during the day but a decrease in temperature at night over the clearing relative to the forest whereas the model shows an increase during the day and night.

In summary we have shown that the model is able to reproduce the important features of the climate of Amazonia associated with forested sites and some aspects for the cleared sites.

5. Results

In this section an assessment will be made of the sensitivity of the final deforested climate to the initial conditions. This is followed by a brief description of the statistical significance test adopted. Analysis of the total deforestation experiment is then presented by building up a picture of the overall response from those experiments which included only certain aspects of the deforestation scenario. First results are presented from the experiment in which albedo alone is increased (INCALB), followed by the experiment in which roughness alone is reduced (REDRGH). The combined impact due to increased albedo and reduced roughness is then compared to the experiment PASTURE in which all vegetation parameters are changed but with the maximum infiltration rate unchanged; this effectively demonstrates the dominance of albedo and roughness changes over the influence of changes in rooting depth, surface resistance and canopy capacity. Then results from the deforestation experiment DEFOREST are presented and compared with results from PASTURE to examine the sensitivity of the regional climate prediction to the change in maximum infiltration rate.

a. Timescale of Adjustment to Initial Conditions

In order to assess the length of time that model variables are likely to be influenced by the initial conditions a Students t-test was performed to assess the statistical significance of the differences between seasons in the first year, (excluding the first 3 months (December to February) when it is accepted that there will definitely be some effect of initial conditions) and a composite of the corresponding season in the following nine years. If large statistically significant differences are found then it would indicate that it is invalid to include these results within the analysis. This procedure was performed on a number of variables that were most likely to retain the longest memory of the initial conditions and evaporation was found to be the most sensitive. Figure 8 shows the difference in

evaporation for the season, June, July, August together with statistically significant results above the 90% level of confidence. Evaporation for this first season is generally lower north of about 5°S and higher south of this latitude compared with the following nine seasons. The area that is statistically significant covers more than 10% of the deforested area and so more than would be expected by chance. This analysis was performed for the preceding and the two following seasons but in each case areas that had greater than a 90% level of significance covered less than 10% of the deforested area. From this assessment it was decided that in order to be certain that the initial conditions were not influencing the final results the first year and 3 months would be excluded from the analysis of the deforestation experiment DEFOREST and the reference experiment FOREST so allowing a total of 9 years for averaging and statistical tests. For those experiments that were run for 5 years and 3 months, only the first 3 months was excluded from the analysis. This was thought sufficient as the primary reason for carrying out these experiments was as an aid to understanding the full deforestation experiment rather than obtaining an accurate estimate of the magnitude of the change. Results will be presented from 9 year averages of FOREST and DEFOREST and 5 year averages of INCALB, REDRGH and PASTURE (a 5 year average of FOREST was used when calculating differences from the latter 3 experiments). Pitman et al. (1993) and Henderson-Sellers et al. (1993) reported a much longer period of adjustment to initial conditions which may have been due to their use of a coupled atmosphere/ocean model rather than an atmosphere model with climatologically varying sea surface temperatures as used here.

b. Statistical Significance of Results

These relatively long simulations (see Table 1) allow a more confident assessment of the statistical significance of the results. The null hypothesis that is put forward is that there has been no change in, for example, rainfall due to deforestation. Student's t statistics for the difference between the annual mean rainfalls for DEFOREST and FOREST are then calculated, using the rainfall data averaged over each year from each experiment. For 9 years (5 years for the other experiments) the number of degrees of freedom is 16 (8) and hence for a 95% confidence level requiring 2½ % in each tail, a test for t less than -2.120

(-2.306) or greater than +2.120 (+2.306) is performed. If this criterion is met then the null hypothesis is rejected and it can be concluded that deforestation is responsible for the change in rainfall at the 95% level of confidence. Regional maps are shown with changes significant at the 95% and 99% level of confidence delineated.

c. Increased Albedo Experiment

The increased albedo experiment INCALB has retained all the vegetation parameters as defined for FOREST except the surface albedo which has been increased to that for DEFOREST - the average change over the year is +0.046. Table 3 shows differences in some climate variables for (INCALB-FOREST).

There is a small decrease in evaporation due to the reduction in net shortwave radiation at the surface. By far the most significant impact is the substantial reduction in rainfall, runoff and moisture convergence. There is a small decrease in surface temperature.

Figure 9 shows the annual mean change in rainfall. Decreases are widespread across the whole of northern South America. Areas of maximum reduction tend to coincide with the location of rainfall maxima. Figure 10 shows the reduction in convergence at about 200m above the surface. Again this reduction in convergence covers the whole of northern South America. This reduction also extends vertically up through the atmospheric column as indicated by the complementary reduction in ascent at 500hPa (Figure 11).

d. Reduced roughness experiment

The reduced roughness experiment REDRGH has retained all the vegetation parameters as defined for FOREST except the roughness length which has been reduced from the FOREST value of 2.1m to the DEFOREST value of 0.026m. Table 3 shows differences in some climate variables for (REDRGH - FOREST).

Evaporation is reduced by a small amount. There is a substantial increase in rainfall and moisture convergence. Surface temperature has risen and there is a consequent increase in

longwave cooling and hence reduction in surface net radiation. The wind at the bottom model level has increased due to the reduction in frictional stress.

Figure 12 shows the annual mean change in rainfall together with the statistical significance of the change. There is a broad band of increase through central southern and western Amazonia. This NW- SE band of increase extends well outside the deforested area into southeastern Brazil. Both these increases and also decreases to the east of Brazil are statistically significant at the 95% level of confidence. Figure 13 shows the changes in divergent flow at 200m and the associated changes in velocity potential. Increased convergence is a very robust feature at all levels within the boundary layer. Figure 14 illustrates that this leads to an increase in ascent at 500hPa corresponding to the areas of increased rainfall. This increase in moisture convergence can partially be explained by the stronger boundary layer winds with weaker frictional stress. Table 3 and Figure 15 show that there is an increase in wind speeds (by 97% near 25m and 40% near 200m).

e. Deforestation experiment with fixed maximum infiltration rate

The deforestation experiment PASTURE has all vegetation parameters modified to the DEFOREST values but the maximum infiltration rate is unchanged.

In this section results will be compared with the combined impact of roughness and albedo to clarify how important these two parameters are in determining the final deforested climate. If these two parameters dominate the final response then by adding together the separate changes due to (INCALB-FOREST) and (REDRGH-FOREST) one would expect to obtain very close agreement with the changes due to (PASTURE-FOREST). Table 3 shows that although the total change in evaporation is in good agreement there are substantial differences in evapotranspiration and interception. The most significant difference is the impact on rainfall where the combined effect of the change in albedo and roughness implies no change in the rainfall whereas PASTURE shows a fairly significant decrease in rainfall. The change in surface net radiation can be more simply attributed to

the combined change in roughness and albedo. The increases in temperature and bottom model level wind speed in PASTURE are due almost entirely to the change in roughness..

Figure 16 is formed by subtracting the sum of the changes due to albedo and roughness ((INCALB-FOREST) + (REDRGH-FOREST)) from the change due to the deforestation scenario with fixed maximum infiltration rate (PASTURE-FOREST) for evaporation and rainfall. Although there are only small differences in evaporation which can probably be attributed to the stomatal resistance and rooting depth changes, discrepancies in rainfall are substantial. Within western Amazonia there are differences of over 1 $mmday^{-1}$. In the absence of substantial evaporation changes, it is unlikely that changes in stomatal resistance, rooting depth and canopy capacity could explain these differences in rainfall and therefore it must be assumed that when a change is made to both albedo and roughness the interaction of the individual responses is non-linear.

f. Deforestation Experiment

The deforestation experiment DEFOREST has all vegetation parameters and the maximum infiltration rate at the soil surface modified. Results from (DEFOREST-FOREST) will be compared with (PASTURE-FOREST).

Table 3 shows that reducing the amount of water that infiltrates the soil in (DEFOREST-FOREST) results in a very large increase in surface runoff in contrast to the decrease in surface runoff when the maximum infiltration rate is unchanged. As less water infiltrates the soil, soil moisture is reduced by a large amount in the DEFOREST experiment whereas soil moisture actually increases by a small amount in the PASTURE simulation. The increase in total runoff, and hence the loss of water from the system, is much greater than for (PASTURE-FOREST). The most significant impact of this much larger reduction in moisture within the system is the large decrease in evapotranspiration. Interception is reduced by similar amounts in both experiments. Overall the reduction in total evaporation is more than double that in the fixed maximum infiltration experiment. This large reduction in evaporation is balanced by an increase in moisture convergence in

contrast to no change in (PASTURE-FOREST). The reduction in rainfall is therefore much less than the reduction in evaporation (about a third). Surface temperature has increased by a much larger amount consistent with the larger reduction in evaporation; this leads to greater longwave cooling and so a larger reduction in surface net radiation.

Figure 17 shows the annual mean changes in rainfall and evaporation together with the statistical significance of these changes, and the moisture convergence (estimated from rainfall-evaporation). Maximum rainfall decreases of over 1mmday^{-1} or up to about 20% of the FOREST rainfall are located near the mouth of the Amazon and show a high level of significance. There are also statistically significant changes outside the deforested area most notably the increases over the coastal regions of northwestern South America. Decreases in evaporation cover most of northern South America with statistically significant decreases over most of the deforested area. Reductions reach 1mmday^{-1} in the southern and eastern parts of the basin.

Figure 18 shows the annual mean changes in rainfall, evaporation and moisture convergence as in Figure 17 but for (PASTURE-FOREST). The most striking difference between these two experiments is in the magnitude of the reduction in evaporation (comparing Figure 18(b) with Figure 17(c)). For both experiments decreases cover most of northern South America but the reductions are much less severe in (PASTURE-FOREST). This is due to the retention of higher soil moisture levels throughout the year when the maximum infiltration is not changed. The pattern of decrease in rainfall is more similar between the two experiments although the area of maximum decrease in rainfall of more than 1mmday^{-1} is shifted towards the west and covers a much larger area. The most important difference is the impact on the moisture convergence. Figure 17(e) (DEFOREST-FOREST) shows a general pattern of increase in moisture convergence over most of northern South America in response to the severe reduction in moisture within the system, compensating to some extent for the reduction in evaporation. Figure 18(c) (PASTURE-FOREST) in contrast, has a large area of reduced moisture convergence

centred over northern South America which tends to exacerbate the reduction in evaporation.

6. Discussion and Summary

The aim of these experiments was to provide a more realistic portrayal of Amazonian deforestation and at the same time a clearer indication of the mechanisms responsible for the deforested climate. The deforestation scenario DEFOREST includes changes to all vegetation characteristics that are specified in the model together with a change to one of the soil parameters - the maximum infiltration rate at the soil surface in accordance with qualitative observations. Recent measurements, taken as part of the ABRACOS field campaigns, provided values for the vegetation characteristics but as no quantitative measurements were available for the change in maximum infiltration rate some estimate had to be made. The reference simulation FOREST, and the DEFOREST experiments were integrated for 10 years and 3 months making these some of the longest experiments of their kind; more confidence can thus be placed in the results as it allows a better assessment of the magnitude of the changes against the natural variability of the system. Another benefit of these relatively long experiments is that it has been possible to exclude those results which may not have reached an equilibrium state whilst still retaining a long time series on which to perform statistical significance tests. Because of the uncertainty in defining the magnitude of the change in maximum infiltration rate, a further experiment PASTURE was run, identical to the deforestation scenario except that the maximum infiltration rate was left unchanged. Experiments including only particular aspects of the deforestation scenario, namely the increase in albedo INCALB and the reduction in roughness REDRGH have led to an improved understanding of the processes at work.

The effect of increased albedo broadly agrees with the Charney (1975) hypothesis; increased albedo following forest removal results in more solar radiation being reflected at the surface; pasture surfaces are warmer and so also emit more longwave radiation to space. The surface-atmosphere column thus loses heat radiatively and so to maintain thermal equilibrium the air must descend and compress adiabatically. For the Amazon

basin this implies reduced ascent and by implication less moisture convergence. Results from INCALB agreed well with this hypothesis, showing that rainfall was reduced in a rather uniform manner across northern South America with decreases of 0.5 to 1.0mm day^{-1} or about 10% in the annual mean with corresponding reductions in moisture convergence. It is interesting to note that the changes were very similar to those obtained by LR in their total deforestation experiment. This can probably be attributed to the rather small change in roughness that they used so allowing the change in albedo to dominate the final results. Dirmeyer and Shukla (1994) showed that average precipitation decreased when the albedo was increased in their tropical deforestation experiment. However, they also found that this result was very sensitive to the magnitude of the increase in albedo; when the albedo was increased by less than 3%, they found that average precipitation was increased.

The response to reduced roughness is less straightforward; results from REDRGH show an increase in moisture convergence leading to a broad band of increased rainfall through central southern and western Amazonia with maximum increases of over $1mmday^{-1}$. These results can be compared with similar experiments carried out by Sud et al (1988) and Lean and Warrilow (1989). Sud et al. obtained decreased convergence and rainfall over northern South America in July with reduced roughness and Lean and Warrilow also reported reduced moisture convergence and rainfall; this was explained by the reduction in roughness leading to a decrease in the turning component of the wind across the isobars and so the moisture convergence into the low pressure systems where rainfall is usually found. As the experiment carried out by Lean and Warrilow was a shorter 8-month experiment, it is difficult to attribute the difference in response to any one cause although a number of differences existed between the models and the experiments. Two of the most likely reasons to explain the differences are the prescribed change in roughness (in this experiment a change of 2.1m was imposed compared with the 0.8m reduction in Lean and Warrilow) and the deficiencies in the earlier climate simulation, notably the overestimation of interception and the re-evaporation of rainfall by the canopy. The disparity between results presented by Sud et al. and this study may be explained by the

lower Andes barrier in their model (typically about half the height of that in our model) (Shukla et al, 1982); with reduced roughness a mountain barrier such as the Andes tends to force the convergence with stronger boundary layer winds, to be contained within the deforested area, whereas in the absence of this barrier all extra downwind convergence and consequent rainfall changes would occur outside this region. This explanation could also partially explain the difference in effect on rainfall between this experiment and LR's experiment as the height of this mountain barrier has been increased in the present version of the model relative to that used by LR. The response to changes in roughness is therefore rather complex and dependent on a number of factors including the model and its climate simulation, the magnitude of the change in roughness and the height of the mountain barrier to the west.

Previous experiments have emphasised the important role of changes to albedo and roughness in determining the final deforested climate. By comparing the combined changes due to INCALB and REDRGH with those due to PASTURE it has been shown that the interaction of the response to each of these two changes together with changes to other vegetation characteristics is highly non-linear. Hence little can be inferred about the overall impact of deforestation unless all parameter changes are suitably represented.

Results from the deforestation scenario DEFOREST fit broadly in line with other recent experiments (see Table 1) indicating reduced rainfall and evaporation and an increase in surface temperature. The predicted increase in moisture convergence is different from many previous deforestation experiments but agrees with Polcher and Laval (1994a) and Manzi (1993) (see Table 1). Increased moisture convergence also agrees with the relationship noted by Polcher (1995), between higher sensible heat flux and increased moisture convergence. The change in moisture convergence is an important finding as one of the key questions it is hoped that GCM experiments can answer is "when evaporation is reduced following deforestation will this lead to a corresponding decrease in rainfall or will moisture convergence act to compensate?". However in this study the change in moisture convergence has been shown to be highly dependent on the extent to which the

soil dries and thereby restricts evaporation. The scale of the differences between the two scenarios DEFOREST and PASTURE was the most surprising result. DEFOREST showed a reduction in average annual evaporation of 0.76mmday^{-1} (18%), substantially more than that for PASTURE of 0.3mmday^{-1} (7%), although average decreases in rainfall were very similar, -0.27mmday^{-1} (4%) for DEFOREST and -0.30mmday^{-1} (5%) for PASTURE. The predicted regional patterns of change in evaporation and rainfall were also very different between the two experiments; most significantly (DEFOREST-PASTURE) showed increased moisture convergence over most of northern South America compensating to some extent for the reduction in evaporation, whereas (PASTURE-FOREST) showed a large area of reduced moisture convergence over northern South America, tending to exacerbate the reduction in evaporation.

This study has gone some way to explaining the important role of changes to a number of key parameters that are used to simulate deforestation in GCMs. Although the focus in previous deforestation experiments has been on the influence of roughness and albedo it has been shown here that a change in the maximum infiltration rate at the soil surface can have a significant impact on the final results. If more credible predictions of the regional changes due to Amazonian deforestation are to be made, it is vital to use precise and representative measurements of all parameters required to define the forest and replacement vegetation.

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Table 1 Comparison of some recent GCM Amazonian deforestation experiments adapted from Pitman et al. (1993)

	Dickinson and Kennedy (1992)	Henderson-Sellers et al. (1993)	Lean and Rowntree (1993)	Nobre at al. (1991)	Manzi (1993)	Polcher and Laval (1994a)	Polcher and Laval (1994b)	This experiment
	CCM1	CCM1-0Z	UKMO	NMC	EMERAUDE	LMD	LMD	UKMO
Resolution	Spectral (R15) 4.5°x7.5°	Spectral (R15) 4.5°x7.5°	Grid 2.5°x3.75°	Spectral (R40) 1.8°x2.8°	Spectral (T42) 2.8°x2.8°	Grid 2.0°x5.6°	Grid 2.0°x5.6°	Grid 2.5°x3.75°
Surface	BATS	BATS	Warrilow (1986)	SIB	ISBA	SECHIBA	SECHIBA	Warrilow(1986)+ interactive resistance + multilayer hydrology
Ocean	mixed layer model	mixed layer model	climatolog-ical SSTs	perpetual december SST	climatological SSTs	climatolog-ical SSTs	observed SSTs 1978-1988	climatological SSTs
Length	3 years	6 years	3 years	1 year	4.2 years	1.1 years	11 years	10 years
Roughness Length	2.0 / 0.05	2.0 / 0.2	0.8 / 0.04	2.65 / 0.08	2.0 / 0.06	no change	2.3 / 0.06	2.1 /0.026
Albedo	0.12 / 0.19	0.12 / 0.19	0.14 / 0.19	0.13 / 0.20	0.13 / 0.20	0.098/0.177	0.14 / 0.22	0.13 /0.18
ΔT (°C)	+0.6	+0.6	+2.1	+2.0	+1.3	+3.8	+0.1	+2.3
ΔP ($mmyr^{-1}$)	-511.0	-588.0	-295.7	-640.0	-15.0	+394.0	-186.2	-157.0
ΔE ($mmyr^{-1}$)	-25.5	-232.0	-198.0	-500.0	-113.0	-985.0	-127.8	-295.7
Change in moisture convergence	decreased	decreased	decreased	decreased	increased	increased	decreased	increased

Table 2 Vegetation and soil characteristics used in the FOREST and DEFOREST experiments

PARAMETER	FOREST			DEFOREST		
Albedo (%)	Month (south of equator)		Month (north of equator)	Month (south of equator)		Month (north of equator)
	Jan	12.6	Jul	Jan	17.5	Jul
	Feb	12.3	Aug	Feb	17.1	Aug
	Mar	12.1	Sep	Mar	18.1	Sep
	Apr	12.4	Oct	Apr	18.4	Oct
	May	13.2	Nov	May	18.7	Nov
	Jun	13.9	Dec	Jun	18.6	Dec
	Jul	14.1	Jan	Jul	19.2	Jan
	Aug	14.4	Feb	Aug	18.7	Feb
	Sep	14.2	Mar	Sep	17.1	Mar
	Oct	14.3	Apr	Oct	17.1	Apr
	Nov	14.1	May	Nov	17.8	May
	Dec	13.4	Jun	Dec	18.0	Jun
	Mean	13.4		Mean	18.0	
Surface resistance (sm^{-1})	Interactive			Interactive		
Rooting depth (m)	2.26			1.5		
Roughness (m)	2.1			0.026		
Canopy capacity (mm)	0.74			0.5		
Vegetation fraction	100%			85%		
Soil moisture conc. at wilting point	0.047			0.047		
Soil moisture conc. at critical point	0.113			0.113		
Soil moisture conc. at saturation point	0.343			0.343		
Saturated hydraulic conductivity (K_s) (kg $m^{-2}s^{-1}$)	0.0026			0.0026		
B exponent used in hydraulic conductivity dependence on soil moisture	3.98			3.98		
Heat capacity ($JK^{-1}m^{-3}$)	2.371×10^6			2.371×10^6		
Heat conductivity ($Wm^{-1}K^{-1}$)	0.531			0.531		
Soil water suction (m)	0.50			0.50		

Table 3 Comparison of 5-year annual mean climate variables using differences averaged over all deforested points

VARIABLE	INCALB - FOREST	REDRGH - FOREST	(INCALB-FOREST) + (REDRGH-FOREST)	PASTURE - FOREST	DEFOREST -FOREST
Total evaporation ($mmday^{-1}$)	-0.14 (-3%)	-0.11 (-3%)	-0.25 (-6%)	-0.3 (-7%)	-0.76 (-18%)
Evapotrans-piration and soil evaporation ($mmday^{-1}$)	-0.09 (-3%)	+0.02 (+1%)	-0.07 (-2%)	+0.13 (+5%)	-0.31 (-12%)
Interception ($mmday^{-1}$)	-0.05 (-3%)	-0.14 (-9%)	-0.19 (-12%)	-0.43 (-28%)	-0.45 (-30%)
Rainfall ($mm\ day^{-1}$)	-0.46 (-7%)	+0.46 (+7%)	0.0	-0.3 (-5%)	-0.27 (-4%)
Moisture convergence ($mmday^{-1}$)	-0.32 (-14%)	+0.57 (+25%)	+0.25 (+11%)	0.0	+0.49 (+22%)
Soil moisture(mm)	-21.9 (-6%)	+23.6 (+7%)	+1.7 (+1%)	13.0 (+4%)	-120.0 (-34%)
Total runoff ($mmday^{-1}$)	-0.44 (-20%)	+0.45 (+20%)	+0.01	+0.03 (+1%)	+0.51 (+23%)
Subsurface Runoff ($mmday^{-1}$)	-0.38 (-22%)	+0.48 (+27%)	+0.1 (+5%)	+0.15 (+9%)	-1.17 (-66.5%)
Surface runoff ($mmday^{-1}$)	-0.06 (-13%)	-0.03 (-6%)	-0.09 (-19%)	-0.13 (-27%)	+1.68 (+350%)
Net radiation (Wm^{-2})	-5.35 (-4%)	-3.91 (-3%)	-9.26 (-7%)	-10.2 (-7%)	-12.7 (-8%)
Sensible heat (Wm^{-2})	-1.42 (-4%)	-0.70 (+2%)	-2.12 (-2%)	-1.51 (+5%)	+9.31 (+28%)
Latent heat (Wm^{-2})	-3.87 (-3%)	-3.20 (-3%)	-7.07 (-6%)	-8.68 (-8%)	-22.0 (-18%)
Horizontal velocity at level 1 (ms^{-1})	+0.01 (+1%)	+1.14 (+97%)	+1.15 (+98%)	+1.17 (+100%)	+1.23 (+105%)
Surface temperature (°C)	-0.09	+1.30	+1.21	+1.38	+2.27

Figure Captions

Figure 1 Model grid for South America showing those points that are defined as forest (F) -all these points are replaced by pasture in the deforestation scenarios. Those points marked with a + are defined as having a constant albedo value all year.

Figure 2 Modelled mean rainfall pattern for the reference experiment FOREST for the months of (a) December, January and February and (c) June, July and August. Observed rainfall pattern over South America (Figueroa and Nobre, 1990) for the months of (b) December, January and February and (d) June, July and August. Contours are at 0, 30, 60, 150, 300, 450, 600, 750, 900, 1050, 1200 then every 300mmmonth^{-1}.

Figure 3 Modelled mean monthly rainfall (single grid point values for FOREST, grid point location in brackets) in mmmonth^{-1} compared with measurements at the three ABRACOS forest sites (a)Manaus (60W, 2.5S) (b)Marabá (48.75W 5.0S) and (c)Ji-Paraná (60W 10S)

Figure 4 Modelled mean monthly quantities (single grid point values for FOREST, grid point location (60W 10S)) compared with measurements at Ji-Paraná (a) net radiation in Wm^{-2} (b) temperature at 1.5m in °C (c) specific humidity at 1.5m in gkg^{-1}

Figure 5 Modelled mean monthly evaporation as a fraction of net radiation for a single grid point (grid point location (60W, 2.5S)), for the current model and averaged over four grid points centred near Manaus for the old version of the model used by Lean and Rowntree (1993) compared with observations for Manaus.

Figure 6 Modelled mean monthly evaporation for FOREST and DEFOREST averaged over rectangular area shown in Figure 1.

Figure 7 Modelled hourly surface temperature for FOREST and DEFOREST for (a) December and (b) July.

Figure 8

(a) Modelled mean difference in evaporation between the June-August period for the first year and a composite for the following 9 years. Contours are at 0.0, +/-0.5, 1.0 and then every 1.0mm day^{-1} with areas of decrease shaded.

(b) Student's t fields showing changes for (a) that are locally significant at the 90% confidence level (solid shaded areas).

Figure 9 Modelled annual mean difference (INCALB - FOREST) in rainfall. Contours are at 0.0, +/-0.5, 1.0 and then every 1.0mm day^{-1} with areas of decrease shaded.

Figure 10 Modelled annual mean difference (INCALB - FOREST) in velocity potential and divergent wind field at about 200m (model level 2) over South America. Contours every 0.1 x $10^6 m^2 s^{-1}$.

Figure 11 Modelled annual mean difference (INCALB - FOREST) in vertical velocity at 500hPa. Contours every 0.006 Pas^{-1}. Positive areas are unshaded and indicate decreased ascent.

Figure 12

(a) Modelled annual mean difference (REDRGH - FOREST) in rainfall. Contours are at 0.0, +/-0.5, 1.0 and then every 1.0mm day^{-1} with areas of decrease shaded.

(b) Student's t fields showing changes for (a) that are locally significant at the 95% (cross hatched shaded areas) and 99% (solid shaded areas) confidence levels.

Figure 13 Modelled annual mean difference (REDRGH - FOREST) in velocity potential and divergent wind field at about 200m (model level 2) over South America. Contours every 0.1 x $10^6 m^2 s^{-1}$.

Figure 14 Modelled annual mean difference (REDRGH - FOREST) in vertical velocity at 500hPa. Contours every 0.006 Pas^{-1}. Negative areas are shaded and indicate increased ascent.

Figure 15 Modelled annual mean difference (REDRGH - FOREST) in winds at about 200m (model level 2). Contours every 1 ms^{-1}.

Figure 16 Modelled annual mean difference (PASTURE - FOREST) - { (INCALB - FOREST)+(REDRGH - FOREST) } for (a) evaporation and (b) rainfall. Contours are at 0.0, +/-0.5, 1.0 and then every 1.0mm day^{-1} with areas of decrease shaded.

Figure 17

Modelled annual mean difference (DEFOREST - FOREST) in (a) rainfall, (c) evaporation and (e) moisture convergence. Contours are at 0.0, +/-0.5, 1.0 and then every 1.0mm day^{-1} with areas of decrease shaded.

Student's t fields showing changes for (DEFOREST -FOREST) in (b) rainfall and (d) evaporation that are locally significant at the 95% (cross hatched shaded areas) and 99% (solid shaded areas) confidence levels.

Figure 18

(a) Modelled annual mean difference (PASTURE - FOREST) in (a) rainfall, (b) evaporation and (c) moisture convergence. Contours are at 0.0, +/-0.5, 1.0 and then every 1.0mm day^{-1} with areas of decrease shaded.

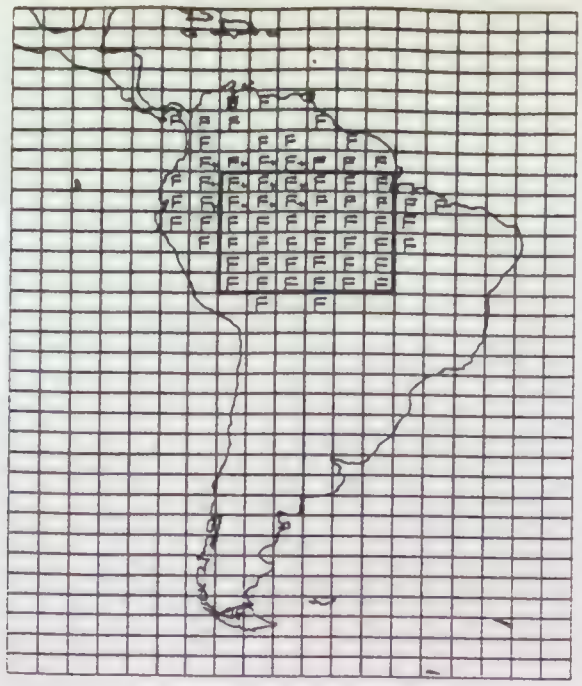


Figure 1

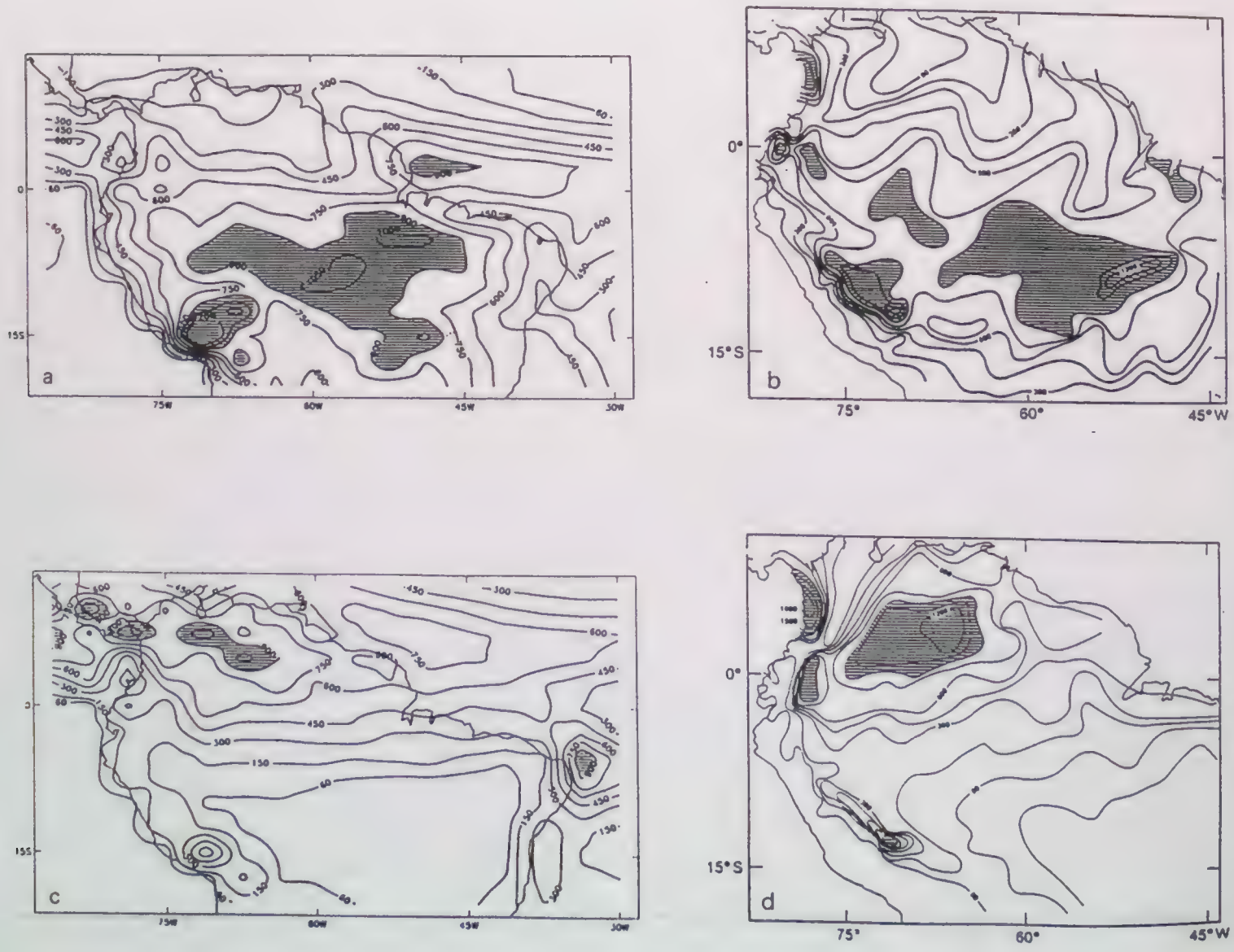


Figure 2

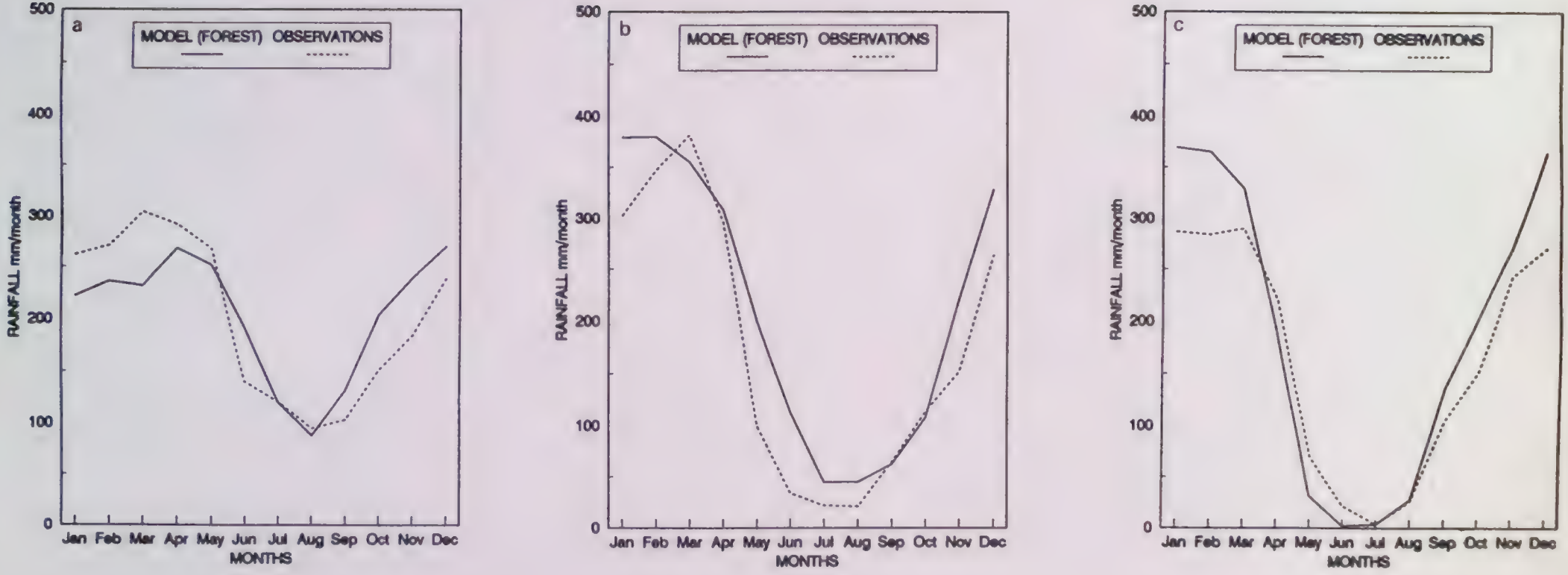

a
MODEL (FOREST) OBSERVATIONS
RAINFALL mm/month
500
400
300
200
100
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
MONTHS
b
MODEL (FOREST) OBSERVATIONS
RAINFALL mm/month
500
400
300
200
100
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
MONTHS
c
MODEL (FOREST) OBSERVATIONS
RAINFALL mm/month
500
400
300
200
100
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
MONTHS

Figure 3

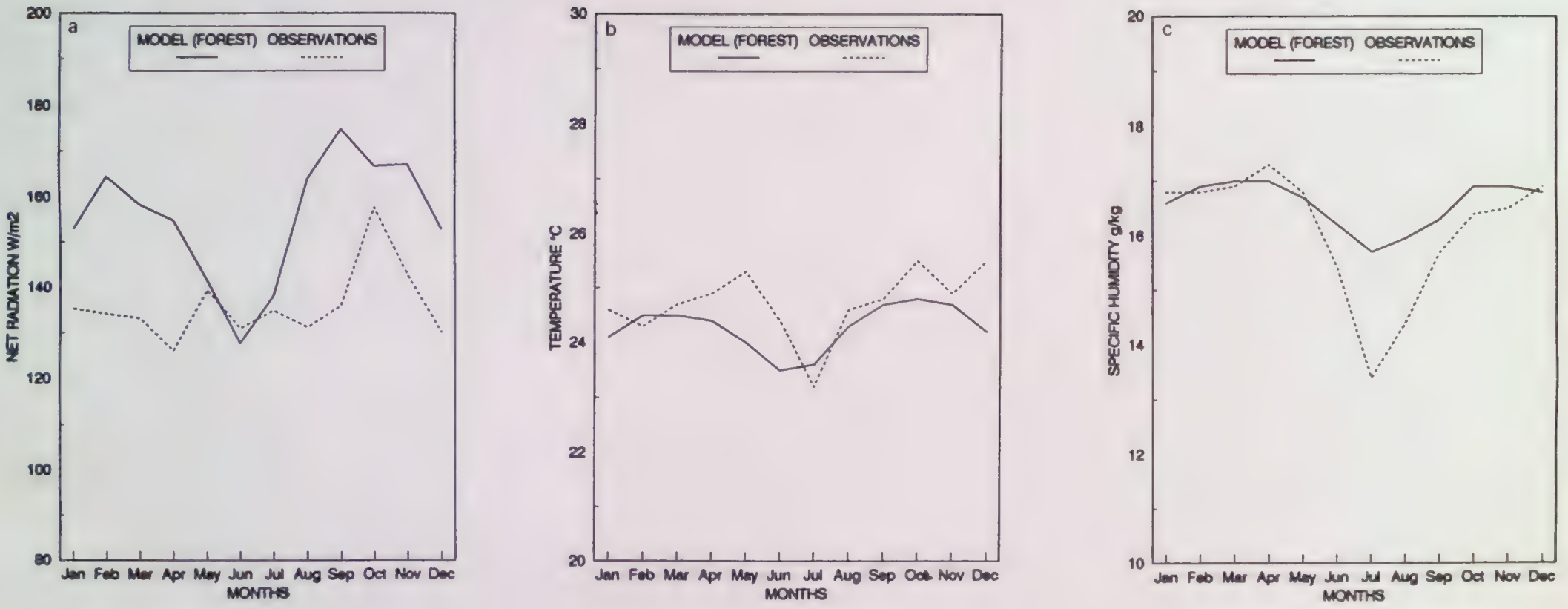

a
MODEL (FOREST) OBSERVATIONS
NET RADIATION W/m2
200
180
160
140
120
100
80
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
MONTHS
b
MODEL (FOREST) OBSERVATIONS
TEMPERATURE °C
30
28
26
24
22
20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
MONTHS
c
MODEL (FOREST) OBSERVATIONS
SPECIFIC HUMIDITY g/kg
20
18
16
14
12
10
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
MONTHS

Figure 4

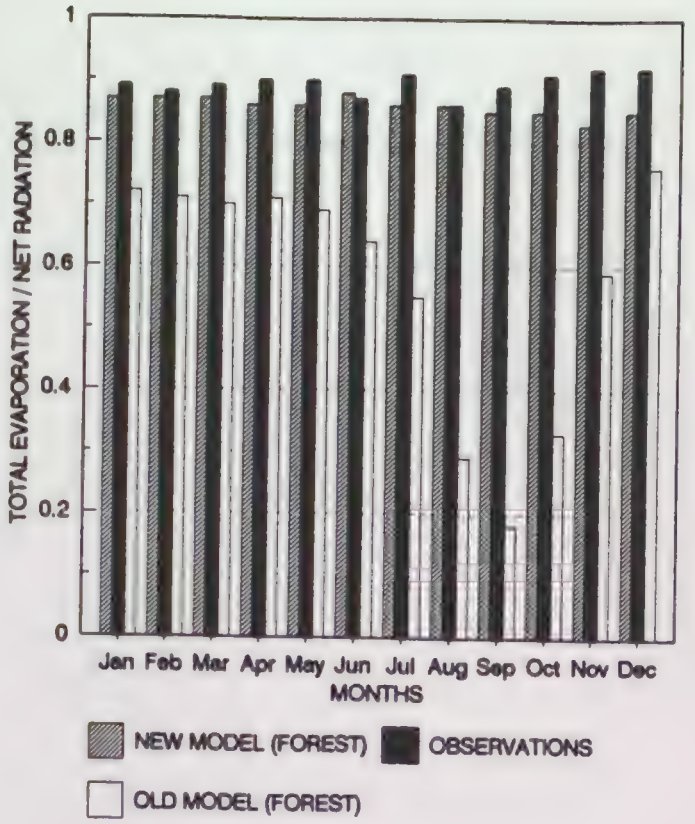


Figure 5

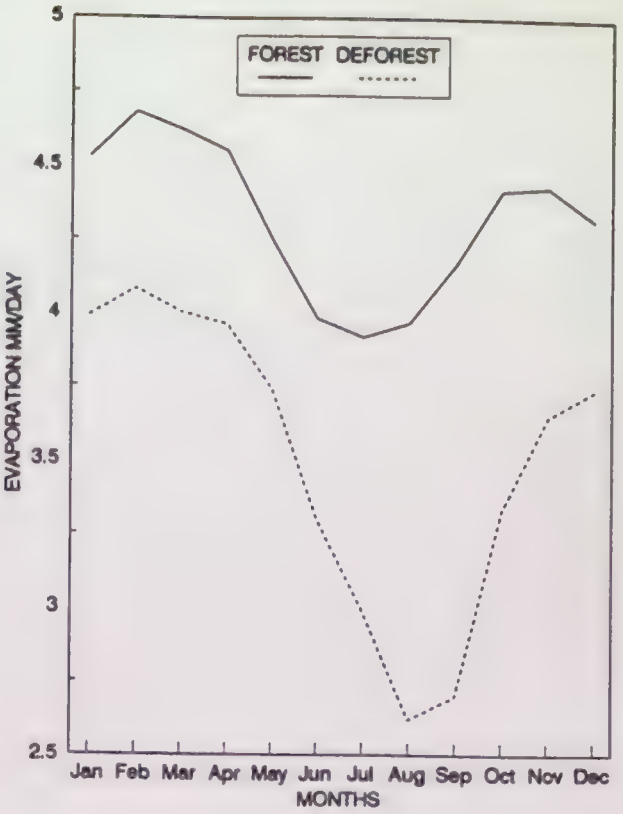
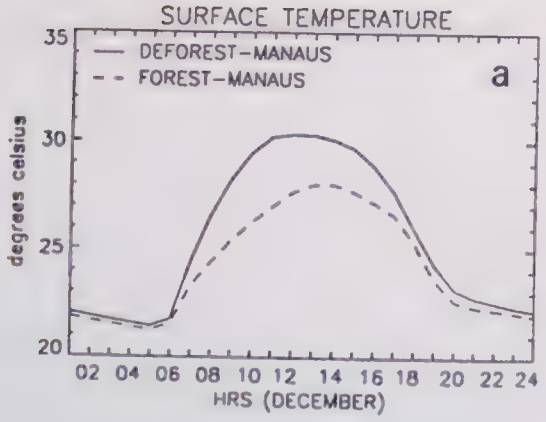


Figure 6



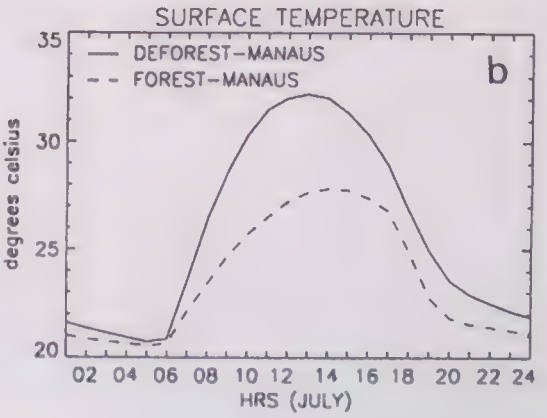


Figure 7

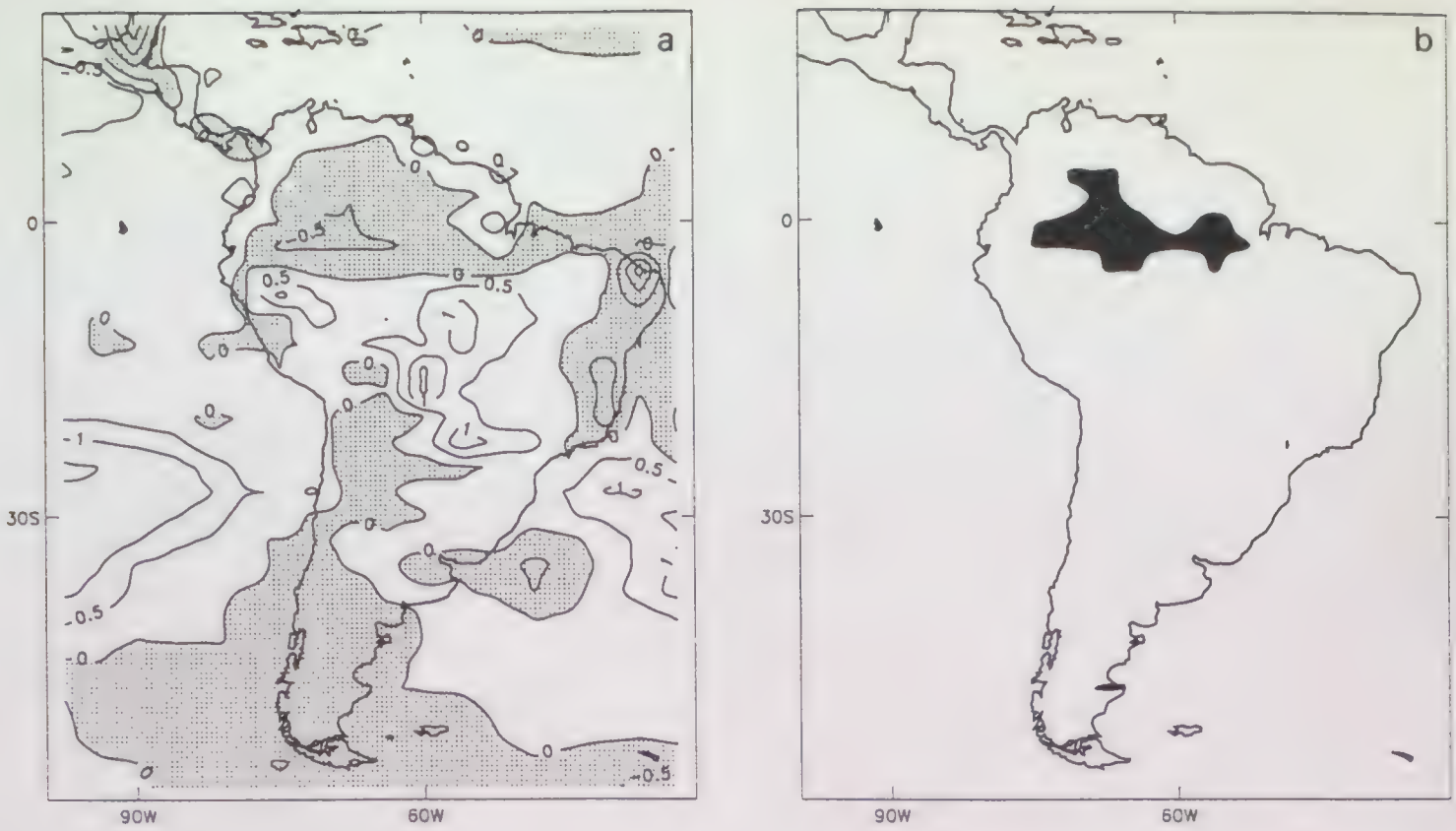
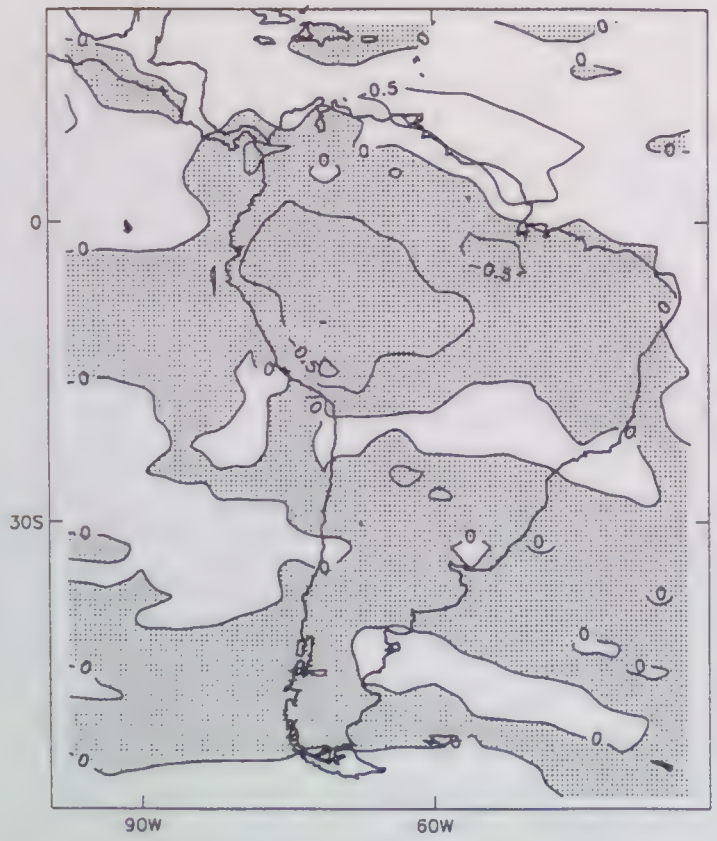


Figure 8



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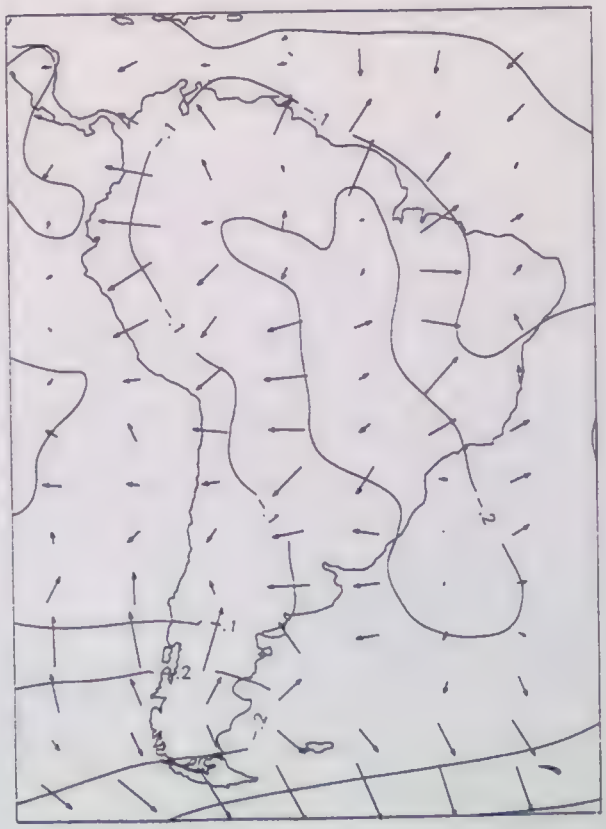

Figure 10

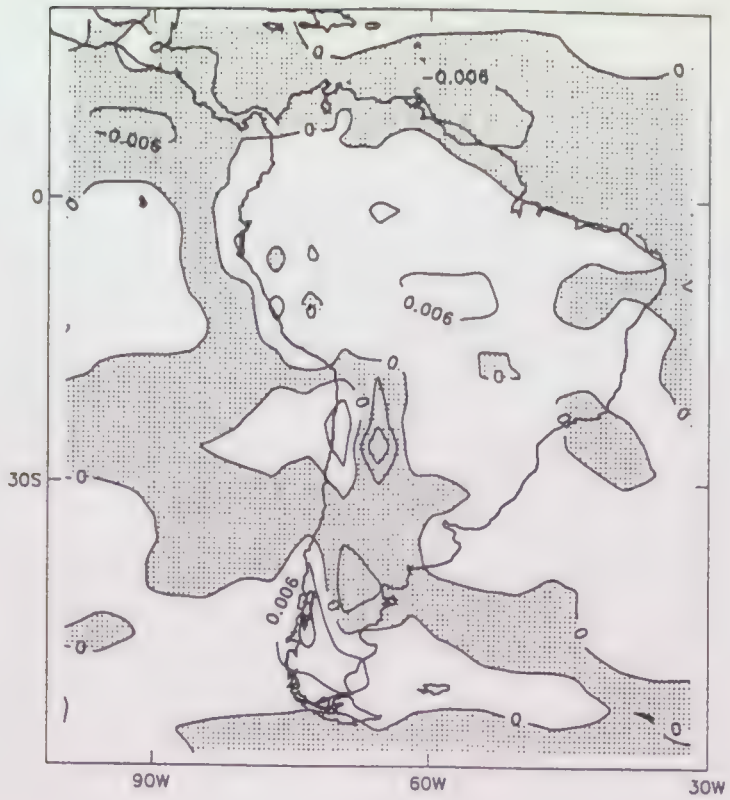

Figure 11

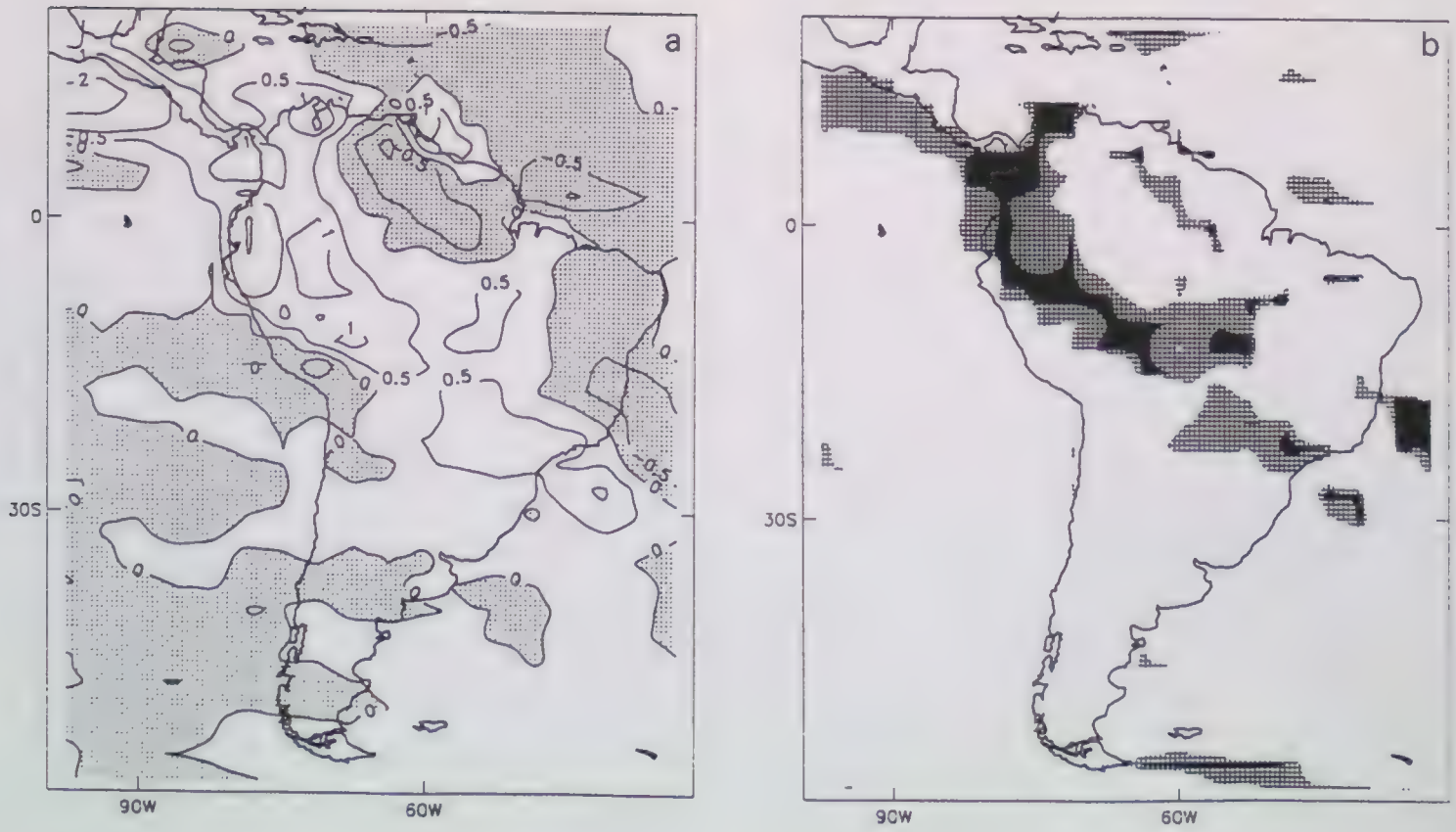

Figure 12

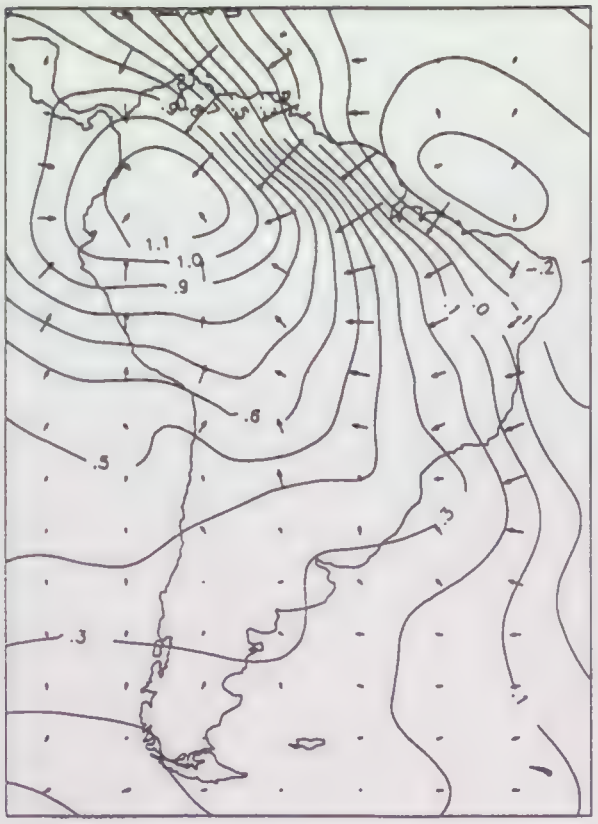

Figure 13

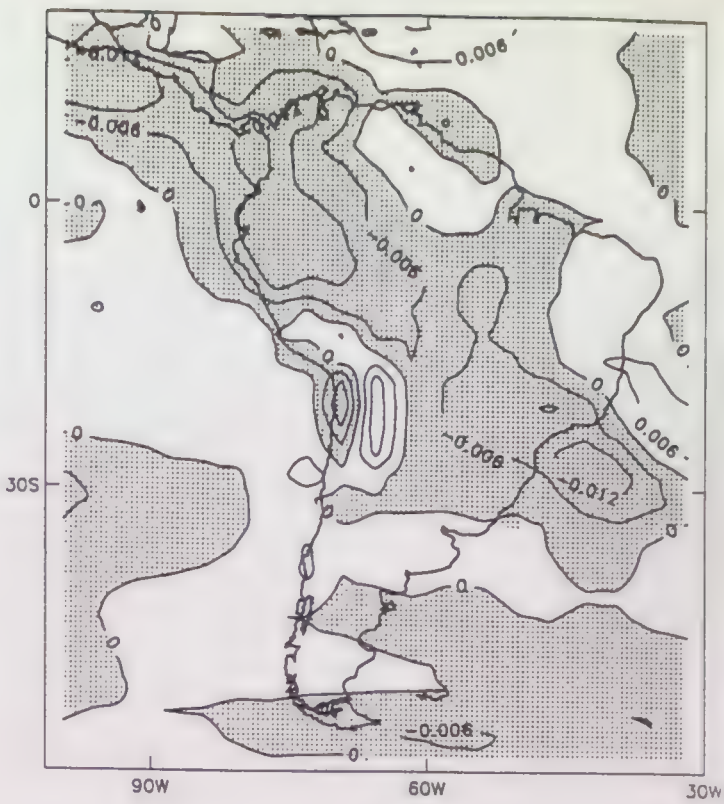

Figure 14

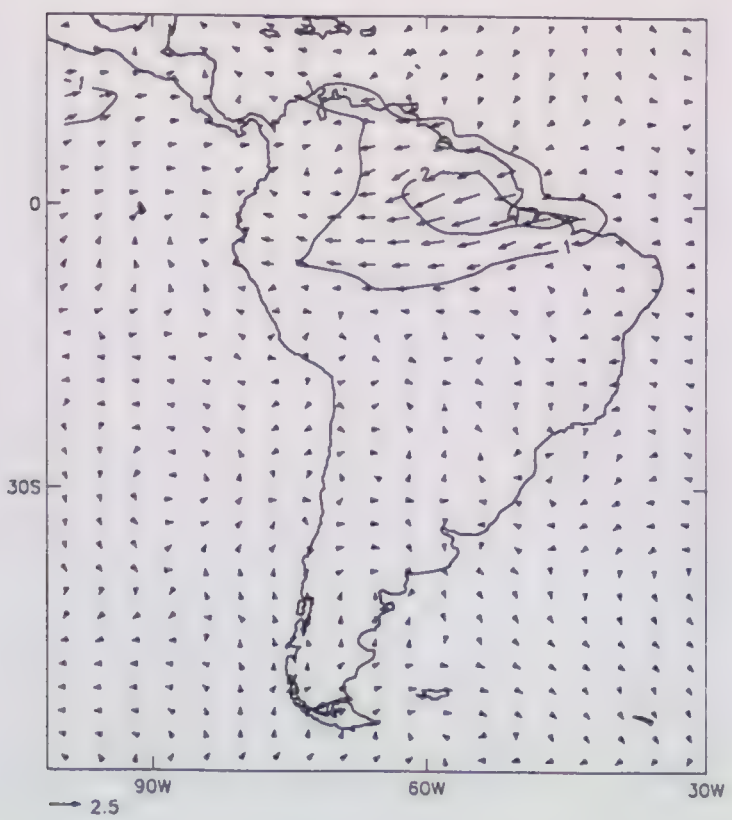

Figure 15

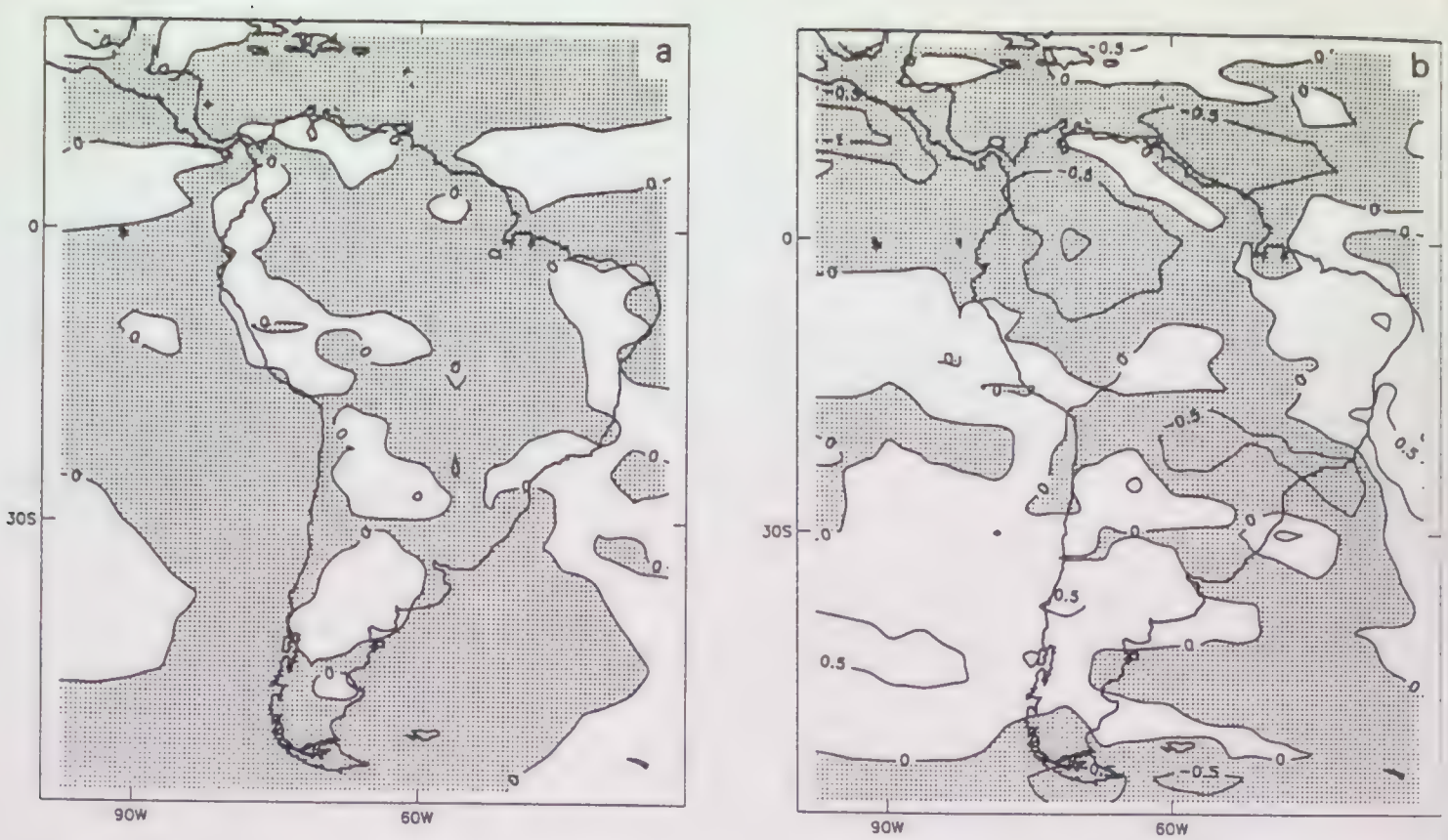

Figure 16

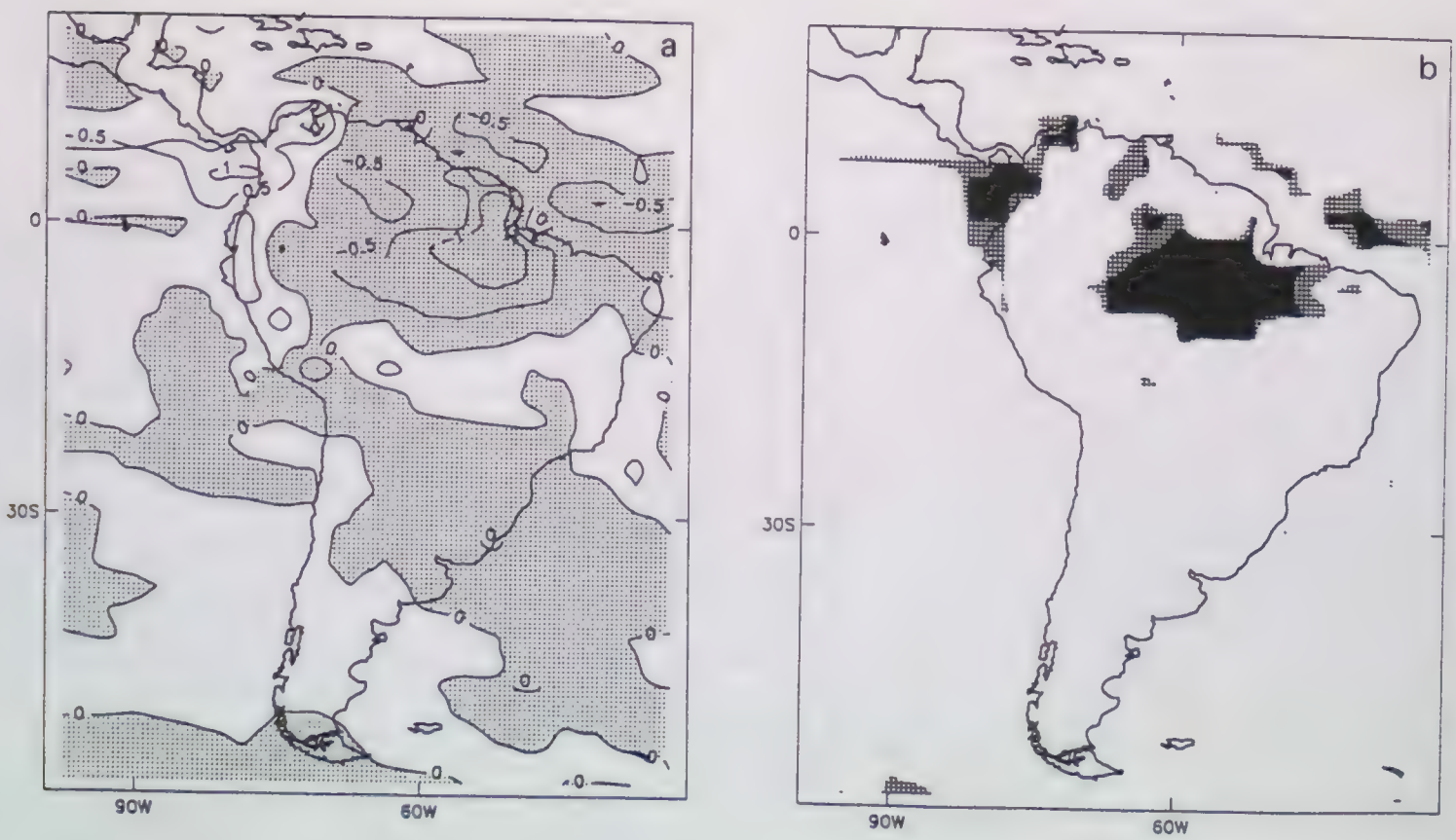

Figure 17

Figure 17

Figure 18

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